Closed-loop Control of Functional Neuromuscular Stimulation

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1. SYNTHESIS OF UPPER EXTREMITY FUNCTION 3

1. A. BIOMECHANICAL MODELING: PARAMETERIZATION AND VALIDATION 3
Purpose 3
Progress Report 3
1. a. i. MOMENT ARMS VIA MAGNETIC RESONANCE IMAGING 3
Abstract 3
Progress Report 3
Reference 7
Plans for next quarter 7
1.a.ii. PASSIVE AND ACTIVE MOMENTS 7
Abstract 7
Purpose 7
Plans for Next Quarter 7
1. B. BIOMECHANICAL MODELING: ANALYSIS AND IMPROVEMENT OF GRASP OUTPUT 8
Abstract 8
Objective 8
Progress Report 8
Plans for Next Quarter 11

2. CONTROL OF UPPER EXTREMITY FUNCTION 11

2. A. HOME EVALUATION OF CLOSED-LOOP CONTROL AND SENSORY FEEDBACK 11
Abstract 11
Purpose 11
Progress Report 11
Plans for Next Quarter 12
2. b. i. ASSESSMENT OF SENSORY FEEDBACK IN THE PRESENCE OF VISION 12
Abstract 12
Purpose 12
Progress Report 12
Plans for Next Quarter 13
2. b. ii. INNOVATIVE METHODS OF COMMAND CONTROL 13
Abstract 13
Purpose 14
Progress Report 14
Plans for Next Quarter 16
2. b. iii . INCREASING WORKSPACE AND REPERTOIRE WITH BIMANUAL HAND GRASP 16
Abstract 16
Purpose 17
Progress Report 17
Plans for Next Quarter 19
2. b. iv CONTROL OF HAND AND WRIST 19
Abstract 19
Purpose 19

1. SYNTHESIS OF UPPER EXTREMITY FUNCTION

The overall goals of this project are (1) to measure the biomechanical properties of the neuroprosthesis user's upper extremity and incorporate those measurements into a complete model with robust predictive capability, and (2) to use the predictions of the model to improve the grasp output of the hand neuroprosthesis for individual users.

1. a. BIOMECHANICAL MODELING: PARAMETERIZATION AND VALIDATION

Purpose

In this section of the contract, we will develop methods for obtaining biomechanical data from individual persons. Individualized data will form the basis for model-assisted implementation of upper extremity FNS. Using individualized biomechanical models, specific treatment procedures will be evaluated for individuals The person-specific parameters of interest are tendon moment arms and lines of action, passive moments, and maximum active joint moments. Passive moments will be decomposed into components arising from stiffness inherent to a joint and from passive stretching of muscle-tendon units that cross one or more joints.

Progress Report

1. a. i. MOMENT ARMS VIA MAGNETIC RESONANCE IMAGING

Abstract

A simulation of the ECU to ECRB tendon transfer has been performed, using published data representing the data that we will measure in individuals who will receive the transfer. The simulation illustrates how the data will be used in our future experiments, and predicts the sensitivity of the resulting wrist moment-angle relationship to the choice of muscle length made during surgery. The simulations show that the choice of length at which the donor muscle is attached to the target tendon has a substantial effect on the range of wrist extension moments that would be produced by the transferred muscle.

Progress Report

We are implementing a method to quantify the outcome that can be expected from tendon transfer surgery. In order to do this we make moment measurements about the wrist while the donor muscle is being stimulated. We then estimate the moment arm of both the donor and the target muscle tendon. Using these presurgical measurements we can simulate the results that can be expected postsurgery.

We are applying this method first to the extensor carpi ulnaris (ECU) to extensor carpi radialis brevis (ECRB) transfer.

The ECU will be stimulated and the moment about the wrist in the flexion/extension as well as radio-ulnar direction will be measured. These measurements will be made using the Wrist Moment Transducer (WMT) as described in previous reports. Measurements will be made at a number of different radio-ulnar angles.

The tendon moment arm of the ECU at these same radio-ulnar angles will be obtained from MRI images using the 3D tendon excursion method as described in previous reports. The tendon moment arm of the ECRB at various flexion-extension angles will also be estimated from MR images using the 3D tendon excursion method.

To illustrate how the measured values will be used to calculate the expected outcome of surgery we use Lieber's model for ECU moment, ECU moment arm and ECRB moment arm instead of the measured values (Loren et al. 1996).

$$M_{ecu} = 1.4 - 0.0041*\theta_{ru} - 0.00086*\theta_{ru}2$$

θ_{ru} is the radio-ulnar angle in degrees and M_{ecu} is the radio-ulnar moment due to stimulated ECU in Nm (Figure 1.a.i.1A)

$R_{ecu} = 28$

For the radio-ulnar direction with the forearm in neutral position, as will be imaged

R_{ecu} is the ECU tendon moment arm in mm (Figure 1.a.i.1B)

Using the ECU moment and ECU moment arm the ECU force at each radio-ulnar angle is calculated

$F_{ecu} = M_{ecu}*1000 / R_{ecu}$

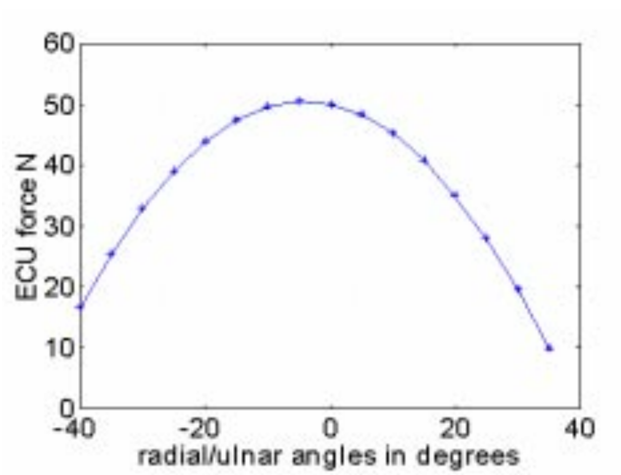
F_{ecu} is ECU force in N (plotted in Figure 1.a.i.1C)

The moment arm is related to excursion and joint angle by R= ds/dθ, where ds is the tendon excursion and dθ is the differential angle. Thus we get ECU excursion by integration with respect to the angle change. The excursion applis to both radio-ulnar angle and flexion extension angle.

Excursion $= \int R_{ecu} * d\theta$

In simulation the excursion is obtained by forward difference approximation over every degree, but in experiments excursion would be measured directly as the change in tendon path length between two joint angles.

Over the range of wrist motion at each position with the ECU force and the excursion we get the force-excursion curve for ECU (Figure 1.a.i.1D)



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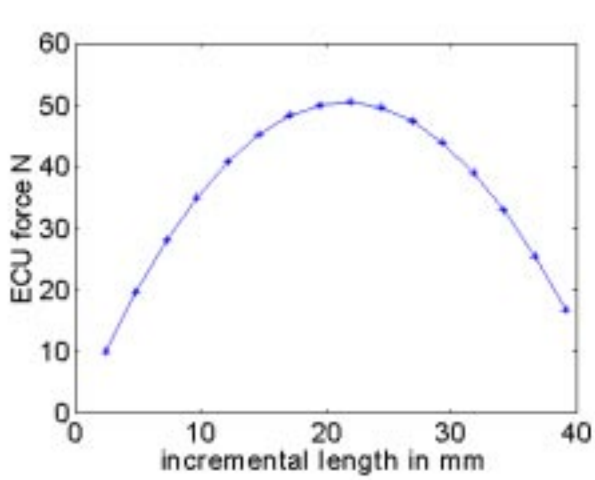

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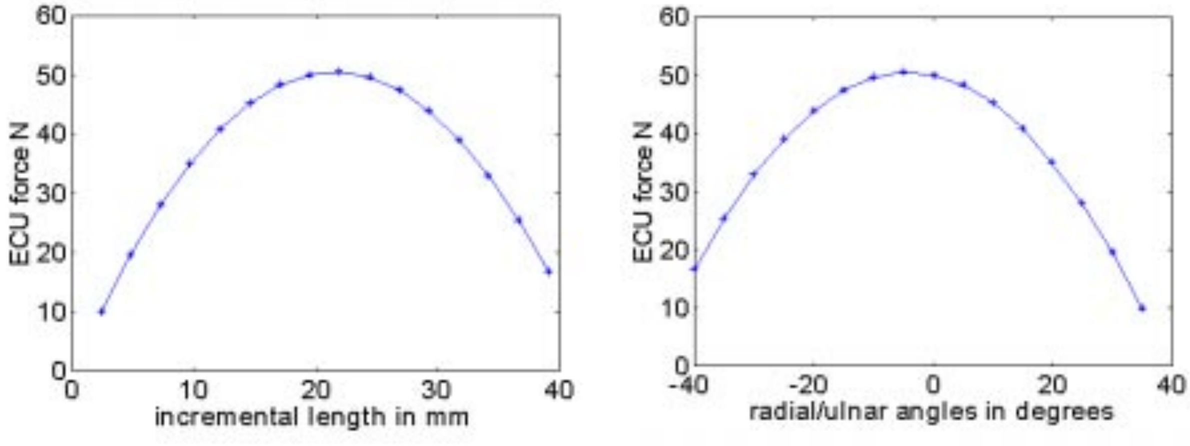


C D

Figure 1.a.i.1. A) ECU moment as a function of wrist position B) ECU tendon moment arm as a function of wrist position C) ECU force as a function of wrist position D) ECU force excursion curve

$R_{ecrb}=16 + 0.16*\theta_{fe} - 0.00087*\theta_{fe}^{2} - 0.000058*\theta_{fe}^{3} - 0.0000012*\theta_{fe}^{4}$

Where θ_{fe} is in degrees in the flexion extension direction and R_{ecrb} is the ECRB tendon moment arm in mm (Figure 1.a.i.2A)

The ECRB excursion is again obtained by integration (simulation) or direct measurement (experimentally).

During tendon transfer surgery the distal end of the ECU tendon is detached and it is sutured to the ECRB, just proximal to the retinaculum. Therefore after tendon transfer surgery the ECU goes through the excursion of the ECRB. From the ECU force excursion curve we obtain the ECU force at the ECRB excursion for various flexion extension angles using a polynomial fit.

$newF_{ecu} = F_{ecu}$ at ECRB excursion (Figure 1.a.i.2B)

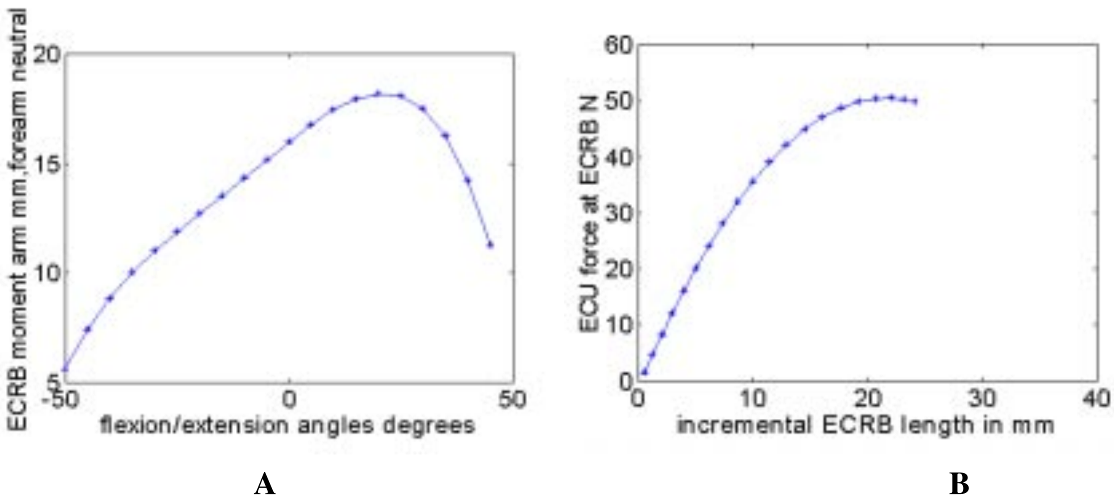


Figure 1.a.i.2. A) ECRB tendon moment arm as a function of wrist flexion extension B) ECU force at the ECRB excursions for wrist flexion extension

Using the ECRB moment arm at various flexion extension angles & the ECU force at these positions we get the moment at the wrist after surgery due to stimulated ECU.

$M_{transfer} = newF_{ecu} * R_{ecrb}$ (Figure 1.a.i.3)

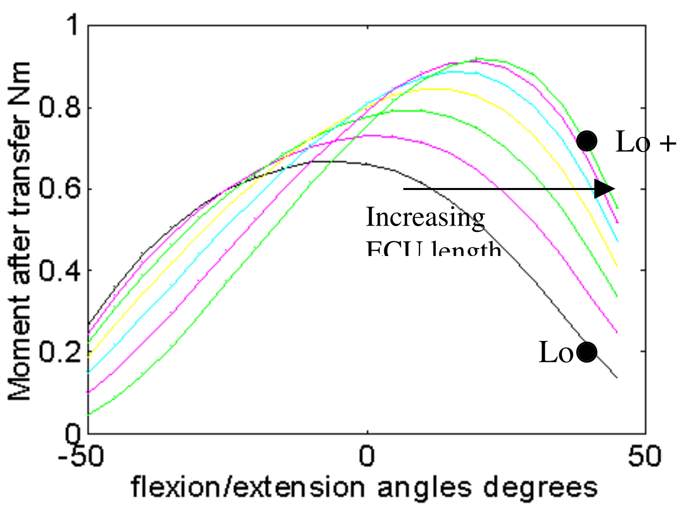


Figure 1.a.i.3) Active extension moment at the wrist expected after surgery, as a function of wrist angle. Each trace represents a different length of ECU set during transfer in increments of 0.24 cm.

We find that using a different reference length Lo for the ECU i.e. setting the ECU to different lengths during the simulations changes the outcome of the surgery.

The peak moment produced as well as the angle at which this peak moment is produced depends on where the ECU is on it's force length curve, which is dependant on the tendon length Lo set during transfer. With a slack transfer the extension moments are small when the wrist is extended, and may not be sufficient to overcome the flexion moments at the wrist thereby decreasing the usefulness. As the wrist moves from an extended position through neutral to the flexed position, the ECU lengthens and acts on the ascending limb of the force excursion curve first, then moves over to the descending limb. With a very tight transfer when the wrist is in flexion the ECU is on it's descending limb and produces little active extension moment. In this case it might not be possible to extend the wrist against the passive and active flexion moments. Also with a very tight transfer the wrist may be pulled into extension and not be able to flex at all, or flexion may cause rupture of the tendon at the transfer site. Thus, there is an ECU length to optimize the results of surgery.

The net moments at the wrist will be the sum of active moments due to the stimulated transfer, passive moments, flexion moments created by the hand grasp system, moments due to gravity and arm orientation and moments due to the load. In order to extend the wrist or maintain an extended wrist position a net extension moment will be needed.

Thus the optimal ECU length can be estimated taking all other moments at the wrist into account.

Reference

Loren, G. J., Shoemaker, S. D., Burkholder, T. J. , Jackobson, M. D., Friden, J., and Lieber, R. L. (1996) Human Wrist Motors: Biomechanical Design and Application to Tendon Transfers, J. Biomechanics, Vol. 29, No. 3 pp. 331-342.

Plans for next quarter

We will continue the application of the biomechanical imaging analysis of tendon moment arms at the wrist. We have imaged able-bodied volunteers, and are examining two individuals with cervical spinal cord injury who might be candidates for the transfer. We are also testing our wrist moment transducer on able-bodied volunteers.

1.a.ii. PASSIVE AND ACTIVE MOMENTS

Abstract

During the past quarter, we reported on preliminary measurements to assess the effect of the positions of each finger on the passive properties of adjacent fingers. We found that the position of the metacarpal phalangeal (MP) joint of the long finger had a very strong influence on the passive properties recorded for the MP joint of the index finger in the single subject studied. The effect was much larger than anticipated. We have now repeated these measurements on four additional subjects. We are in the process of analyzing this data, which appears to show a range of effects. This data will be analyzed and the results will be presented next quarter. We expect to be able to identify whether the influence between digits is due to the stretching of the skin or through linkages between the tendons and muscles.

Purpose

The purpose of this project is to characterize the passive properties of normal and paralyzed hands. This information will be used to determine methods of improving hand grasp and hand posture in FES systems.

Plans for Next Quarter

During the next quarter, we will analyze the data we have obtained from the five normal subjects to evaluate the influence of adjacent finger position on the passive properties of the MP joint. We will also perform additional experiments with normal and paralyzed individuals.

1. b. BIOMECHANICAL MODELING: ANALYSIS AND IMPROVEMENT OF GRASP OUTPUT

Abstract

Neuroprosthesis users require strong voluntary wrist extension to overcome the wrist flexion moment generated by the finger flexors during electrical stimulation and because many users rely on a wrist controller to control hand opening and closing. It is common to transfer the distal tendon of the brachioradialis, an elbow flexor, to the distal tendon of the extensor carpi radialis brevis, one of the primary wrist extensors, to promote voluntary wrist extension. We are currently using a graphics-based computer model of the upper extremity to assess muscle function after a brachioradialis to extensor carpi radialis brevis tendon transfer (Br-ECRB).

Objective

The purpose of this project is to use the biomechanical model and the parameters measured for individual neuroprosthesis users to analyze and refine their neuroprosthetic grasp patterns.

Progress Report

In the past quarter, we have evaluated how the force- and moment-generating properties of a tight and slack Br-ECRB transfer (described in previous progress reports) influence the ability to extend the wrist. In particular, we calculated the range of elbow postures over which the wrist could be maintained in 40˚ wrist extension for both surgical techniques. 40˚ wrist extension is a position which closes the hand via the tenodesis grasp, and the ability to maintain this wrist position would indicate an individual could potentially grasp and hold an object.

The joint moment required to maintain the wrist in 40˚ extension is determined by the gravitational moment produced by the weight of the hand and the passive properties of the wrist joint in this position. The gravitational moment is determined by the weight of the hand and the perpendicular distance between the center of mass of the hand and the wrist joint center (i.e., the moment arm). The gravitational moment of the weight of the hand was calculated using regression equations (McConville *et al.*, 1980) which determined the mass of the hand and the location of the center of mass for a 50^{th} percentile male (180 cm, 75 kg). The distance between the center of mass of the hand and the center of the wrist joint was calculated using the musculoskeletal model of the upper extremity. The joint moment required to maintain the wrist in 40˚ extension was calculated by summing the gravitational moment of the hand with measurements of passive wrist joint properties from an individual with C5 level tetraplegia (Lemay and Crago, 1997).

The wrist extension moment necessary to maintain the wrist in 40˚ wrist extension (for a 50^{th} percentile male with SCI passive joint properties) was compared to the moment-generating properties of the slack and tight Br-ECRB transfer, estimated using the biomechanical model (Fig. 1.b.1). The model simulations indicate that the tight transfer increases the elbow range of motion where wrist extension can be maintained by 20˚. The extra 20˚ provided by the tight transfer could be very important functionally; if wrist extension cannot be maintained, the hand opens. Without the extra 20˚, the person may lose their grip on an object before the elbow is flexed enough to bring the object close to the body. Thus, the tight transfer could provide the difference between eating independently and needing assistance.

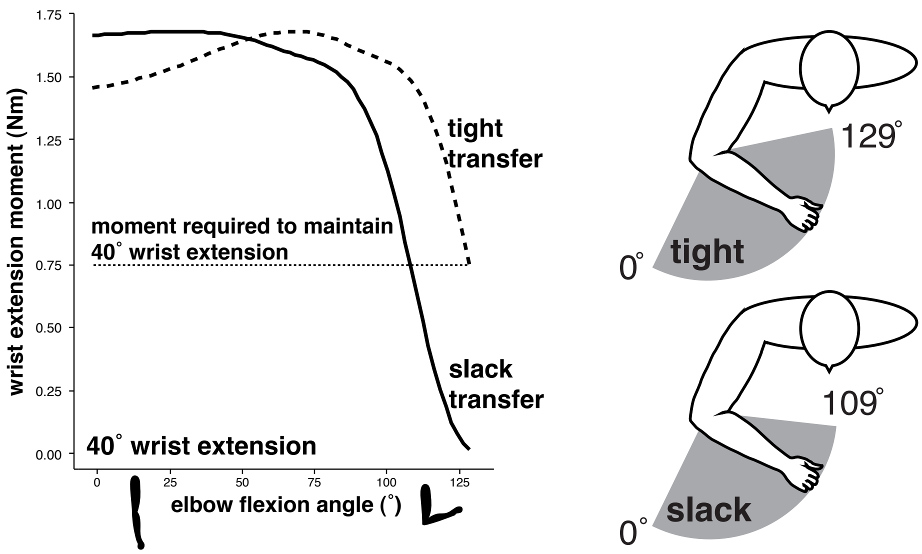


Figure 1.b.1. The figure on the left compares the wrist extension moment generated by the slack and tight transfers with the moment required to maintain the wrist in 40˚ wrist extension. The functional consequences are illustrated on the right; the shaded area indicates the range of elbow postures where 40˚ wrist extension can be maintained. The tight transfer can maintain wrist extension and bring the hand close to the body. The model indicates the tight transfer could provide the difference between eating independently and needing assistance.

Intuitively, the joint moment necessary to maintain the wrist in extension will increase if an object is being held in the hand. We also compared the moment-generating properties of the slack and tight transfers with the wrist extension moment necessary to balance the weight of the hand, the passive wrist flexion moment from an individual with C5 level tetraplegia, and weights ranging from 1.1kg (0.5 lbs) to 2.75 kg (1.25 lbs, Fig. 1.b.2). As the weight of the object being held increases, the range of elbow postures where wrist extension can be maintained decreases for both surgical techniques (Fig. 1.b.3). For the lighter weights (1.1 kg and 2.2 kg), the tight transfer provides a greater range of elbow postures where wrist extension can be maintained. For the 2.75 kg weight, however, the moment-generating capacity of the tight transfer in extended positions is not sufficient to extend the wrist, and the slack transfer provides a greater range of elbow postures where 40˚ of wrist extension can be maintained. In general, the range of elbow postures where 40˚ of wrist extension can be maintained is limited for both transfers in the 2.75 kg (1.25 lb) weighting condition.

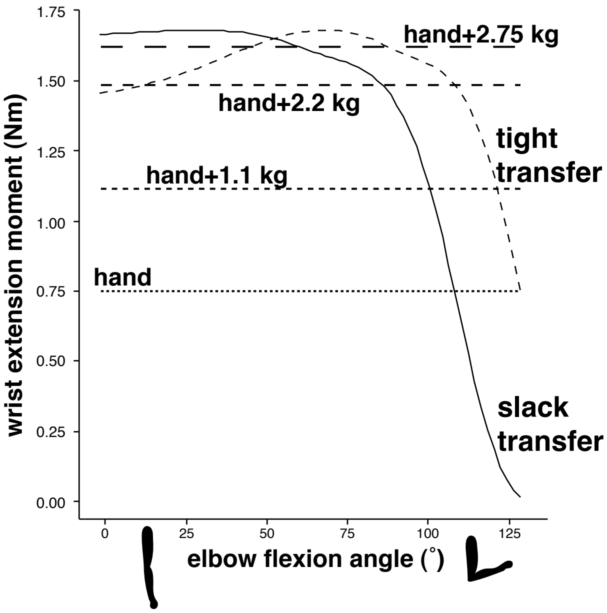


Figure 1.b.2. Comparison between the wrist extension moment generated by the slack and tight transfers with the moment required to maintain the wrist in 40˚ wrist extension (hand), the moment required to maintain the wrist in 40˚ extension when holding a 0.5 lb object (hand+0.5 lb), a 1.0 lb object (hand+1.0 lb), and a 1.25 lb object (hand+1.25 lb). The wrist extension moment required to maintain an extended wrist and hold an object increases with the weight of the object.

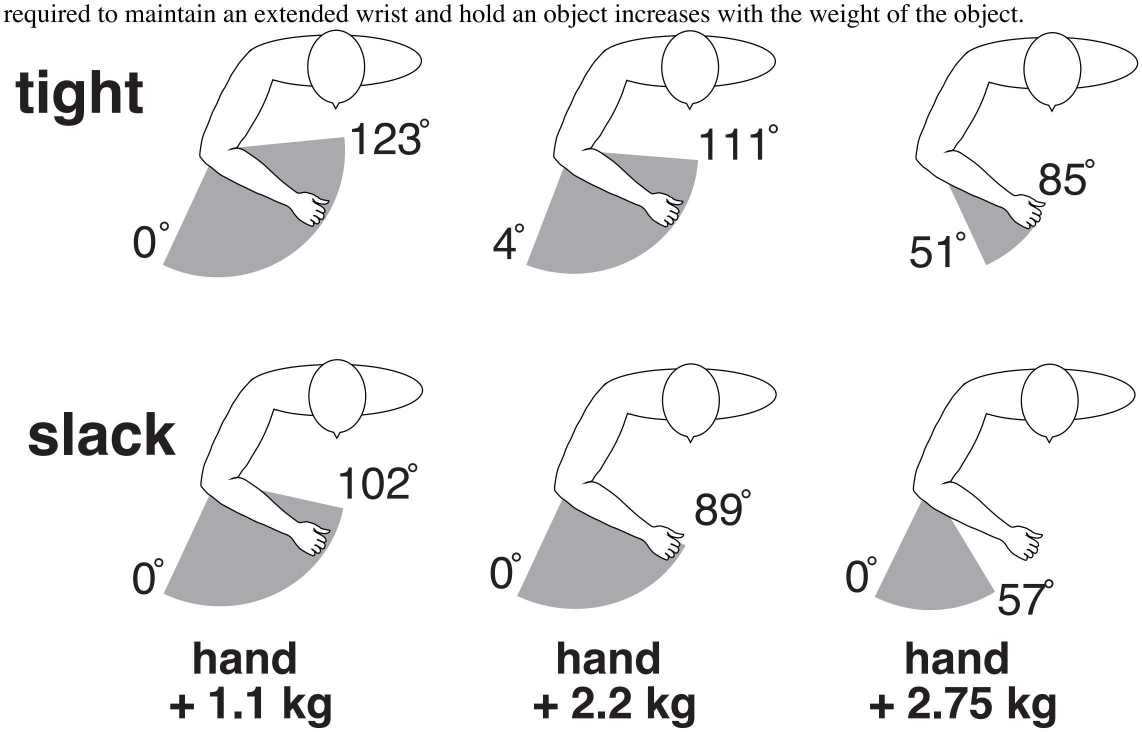


Figure 1.b.3. The range of elbow postures where 40˚ wrist extension can be maintained by the tight and slack transfer in 3 different weighting conditions. The range of motion where wrist extension can be maintained decreases with the weight of the object for both surgical techniques.

Plans for Next Quarter

In the next quarter, we plan to further investigate the effects of surgical tensioning of the Br-ECRB transfer on wrist function. We plan to evaluate how the differences in passive moment-generating properties between the two surgical techniques influence the range of elbow postures where gravity-assisted wrist flexion can be achieved.

References

McConville, J. T., Churchill, T. D., Kaleps, I., Clauser, C. E., and Cuzzi, J. (1980) Anthropometric relationships of body and body segment moments of inertia. Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Yellow Springs, OH, Technical Report AFAMRL-TR-80-119.

Lemay, M. A. and Crago, P. E. (1997) Closed-loop wrist stabilization in C4 and C5 tetraplegia. *IEEE Transactions on Rehabilitation Engineering* **5**:224-252.

2. CONTROL OF UPPER EXTREMITY FUNCTION

Our goal in the five projects in this section is to either assess the utility of or test the feasibility of enhancements to the control strategies and algorithms used presently in the CWRU hand neuroprosthesis. Specifically, we will: (1) determine whether a portable system providing sensory feedback and closed-loop control, albeit with awkward sensors, is viable and beneficial outside of the laboratory, (2) determine whether sensory feedback of grasp force or finger span benefits performance in the presence of natural visual cues, (of particular interest will be the ability of subjects to control their grasp output in the presence of trial-to-trial variations normally associated with grasping objects, and in the presence of longer-term variations such as fatigue), (3) demonstrate the viability and utility of improved command-control algorithms designed to take advantage of forthcoming availability of afferent, cortical or electromyographic signals, (4) demonstrate the feasibility of bimanual neuroprostheses, and (5) integrate the control of wrist position with hand grasp.

2. a. HOME EVALUATION OF CLOSED-LOOP CONTROL AND SENSORY FEEDBACK

Abstract

The purpose of this project is to deploy an existing portable hand grasp neuroprosthesis capable of providing closed-loop control and sensory feedback outside of the laboratory. We have completed the development of a stand alone, analog, single channel stimulator for grasp-force feedback. A working hard-wired, battery powered prototype has also been built. Details will be reported next quarter

Purpose

The purpose of this project is to deploy a portable hand grasp neuroprosthesis capable of providing closed-loop control and sensory feedback outside of the laboratory. Our goal is to evaluate whether the additional functions provided by this system benefit hand grasp outside of the laboratory.

Progress Report

See Abstract.

Plans for Next Quarter

In the next quarter, we will perform field testing on the analog single-channel feedback system using able-bodied volunteers and neuroprosthesis users (if possible). We will also prepare documentation for discussions with potential internal and external short-run manufacturers regarding construction of 5-10 devices.

2. b. INNOVATIVE METHODS OF CONTROL AND SENSORY FEEDBACK

2. b. i. ASSESSMENT OF SENSORY FEEDBACK IN THE PRESENCE OF VISION

Abstract

The purpose of this project is to develop a method for including realistic visual information while presenting other feedback information simultaneously, and to assess the impact of feedback on grasp performance in the presence of such visual information. In this quarter, we completed the technical development of the project and collected a complete library of video clips suitable for our evaluation purpose. The experimental protocol for the evaluation task was defined and preliminary data from five subjects was collected.

Purpose

The purpose of this project is to develop a method for including realistic visual information while presenting other feedback information simultaneously, and to assess the impact of feedback on grasp performance. Vision may supply enough sensory information to obviate the need for supplemental proprioceptive information via electrocutaneous stimulation. Therefore, it is essential to quantify the relative contributions of both sources of information.

Progress Report

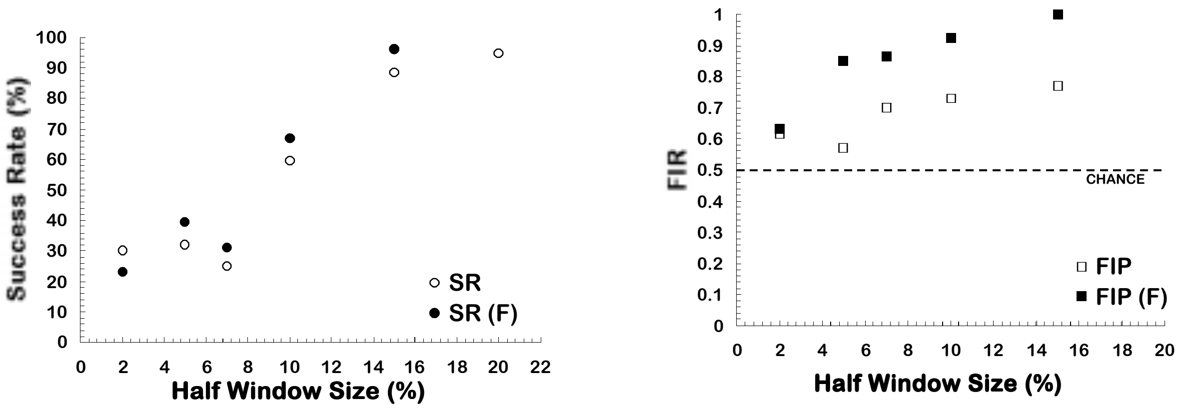
We have started to collect data from able-bodied subjects using our previously discussed Evaluation System. A brief review is reproduced below to introduce the new experimental protocol.

Subjects don a shoulder controller and are asked to acquire a predetermined force while viewing a digitized video clip of a real neuroprosthesis user's hand. The pre-determined force is specified as a target command in the evaluation software and the break and slip forces are entered as an error window size. Thus if the target command is 70% and the window size specified is 5% the slip force would lie at 65% command and the break force would lie at 75% command. The software looks up the corresponding target, break, and slip forces from an averaged recruitment curve specific to the video clips' library.

Each evaluation trial consists of an acquire and a hold phase. Our trials are set to last 10 seconds and the acquire-to-hold ratio is set to 1/2. The current task parameter values were chosen to be representative of a typical grasping task encountered by neuroprosthesis users. A success in the acquire phase is marked by the force lying within the break force and slip force bounds (the error window) at the end of the phase, and a success in the hold phase is marked by the force lying within the error window for the entire duration of the phase.

The subject is asked to perform 5 familiarization trials during which they have knowledge of the target force, error window, and the force they are generating. This is facilitated by simultaneously presenting a view of the evaluation task window and the neuroprosthesis clip. Subsequently the subject is asked to concentrate on the video clip alone and perform a block of twenty trials at the given force parameters. This process is repeated for 4~5 blocks of decreasing window sizes. The subject is then provided with force feedback in the form of electrocutaneous stimulation and asked to repeat the blocks respectively. Success rates are plotted as a function of window size.

At the end of every trial the outcome of the trial is recorded as a success or a failure and the subject is asked if the trial was a success or a failure. Their decision is verified and if the task outcome was a failure the subjects are also asked whether the force they generated was too high, or too low. This is also verified by the investigator. These responses are used to calculate the Failure Identification Rate (FIR) for the subject. We define the FIR as the proportion of trials correctly identified as being too high or too low given that the task was a failure.



a b

Fig. 2.a.i.1 Pooled success (a) and failure identification (b) rates of 5 subjects

Fig. 2.a.i.1 shows the data that has been collected from five subjects over two sessions. The filled markers represent the results with feedback and the open markers represent the results without feedback. The data expresses substantial variablility across subjects and over sessions i.e. for some subjects there is no observable increase or decrease in task performance with feedback as compared to that without feedback while for some subjects there is a consistent increase in performance with feedback. If we pool the data over subjects and over sessions we observe a modest increase in the success rate with feedback as compared to that without feedback (Fig. 2.a.i.1a). We also observed a consistent increase in the pooled FIR of the subjects with feedback as compared to that without feedback (Fig. 2.a.i.1b). However, the individual subject FIR's also showed a lot of variability within and across subjects.

An attempt was made to fit a logistic regression to the data, however, the residues were too large to warrant such a fit. We are currently looking at different link functions for a modified logistic regression fit.

Plans for Next Quarter

We will be collecting more data from able–bodied subjects using the current library of video clips. We will then analyze the data statistically to test for significance of results. In addition we will be scheduling another neuroprosthesis user to enhance the library of video clips.

2. b. ii. INNOVATIVE METHODS OF COMMAND CONTROL

Abstract

The purpose of this project is to develop new command control algorithms that will make the control of the hand simpler and more effective and to assess the impact of these new algorithms on the ease of control of the hand. In this quarter, the existing video based evaluation system was modified to include the ability to lock the grasp at a set command level and a new command control algorithm, rectified

lock, was implemented. Experiments were conducted to evaluate the effectiveness of the system and algorithm. The results demonstrate that the video based evaluation system was a useful tool to screen new command control algorithms and suggest that rectified lock, in its current form, may not be an improvement over the presently used proportional control.

Purpose

The purpose of this project is to improve the function of the upper extremity hand grasp neuroprosthesis by improving user command control. We are specifically interested in designing algorithms that can take advantage of promising developments in (and forthcoming availability of) alternative command signal sources such as EMG, and afferent and cortical recordings. The specific objectives are to identify and evaluate alternative sources of logical command control signals, to develop new hand grasp command control algorithms, to evaluate the performance of new command control sources and algorithms with a computer-based video simulator, and to evaluate neuroprosthesis user performance with the most promising hand grasp controllers and command control sources.

Progress Report

The video based evaluation system (see 2.b.i) was modified to include the ability to lock the grasp at a set command level and a new command control algorithm, rectified lock, was implemented. Locking the hand causes the neural prosthesis to maintain the command level that was present at the time the lock signal was received. This results in a constant grasp output regardless of the position of the contralateral shoulder, which was used as the source of the control signal.

A peak detection algorithm was implemented to generate a lock signal. In this algorithm, an array containing the twenty prior command inputs is stored. Arrays containing the size of movement for the twenty prior points and the velocity, or rate of change of command, at that point are also stored. To initiate a lock signal, the user must have maintained a movement size below an activity threshold for a specific amount of time followed by a movement size above a locking threshold value. The user must also have generated a shoulder velocity greater than a threshold, and that must have been followed by a negative velocity. If all of the these conditions are met, then the command at the time that the lock signal was initiated becomes the locked value. The same motion is used to turn off the lock.

Several thresholds must be determined to use this algorithm, and suitable values for these thresholds vary from person to person. A method has been implemented to enable setting of the thresholds for each user. In this routine, the user is asked to make five locking movements with the controlling shoulder. The movements are recorded, and the accompanying velocities, movement sizes, and delay times are averaged over the five trials to help determine the threshold values which would optimize performance for the user.

A new command control algorithm, called rectified lock, was also implemented in the video based evaluation system. The rectified lock (or ratchet) algorithm allows the user to further increase force output after locking the hand, but does not allow the user to decrease the force unless the hand is unlocked (fig. C.2.b.ii.1). This algorithm allows the user to lock at a low force value, and slowly increase the force until the desired force output is achieved.

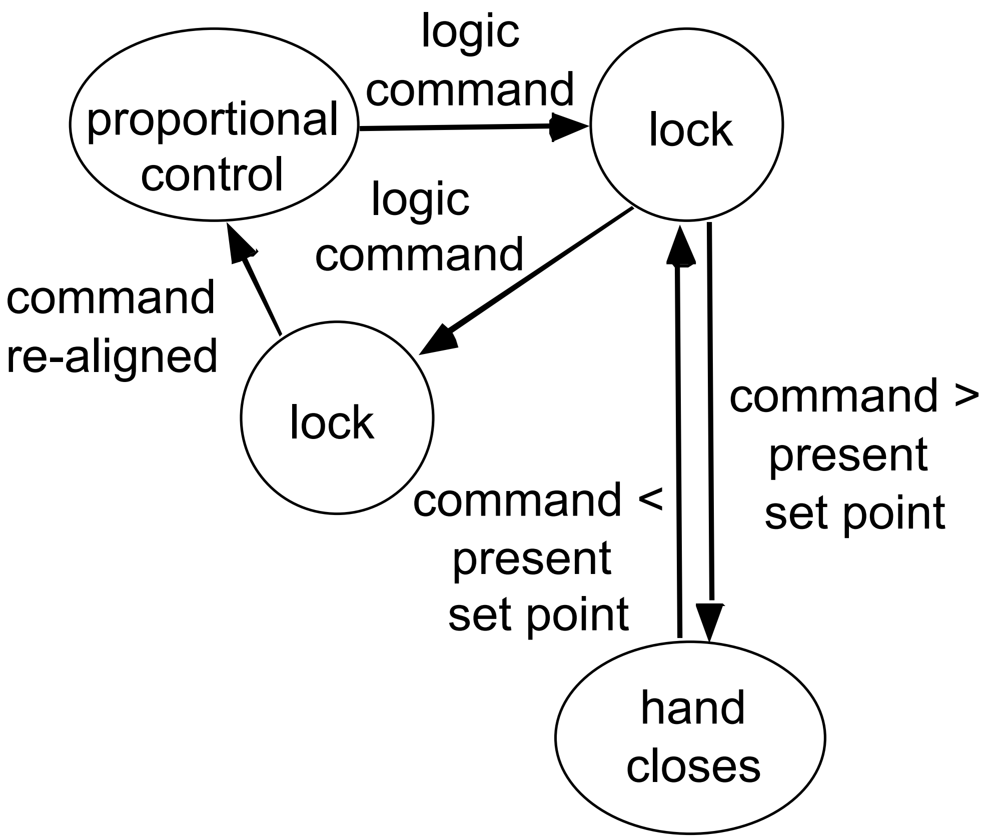


Figure 2.b.ii.1 State diagram of the rectified lock command control algorithm. The subject uses the position of the contralateral shoulder as a proportional control signal. Logic commands are detected from rapid elevations or depressions of the shoulder.

During this quarter the video based evaluation system was used to compare the performance of the new rectified lock algorithm to the traditional proportional control algorithm in an acquire and hold task. In this task the subject must increase the grasp force to a specified window within a specified time period (3.33 s) and hold it in that window for a specified interval (6.67 s) using only visual feedback and shoulder proprioception.

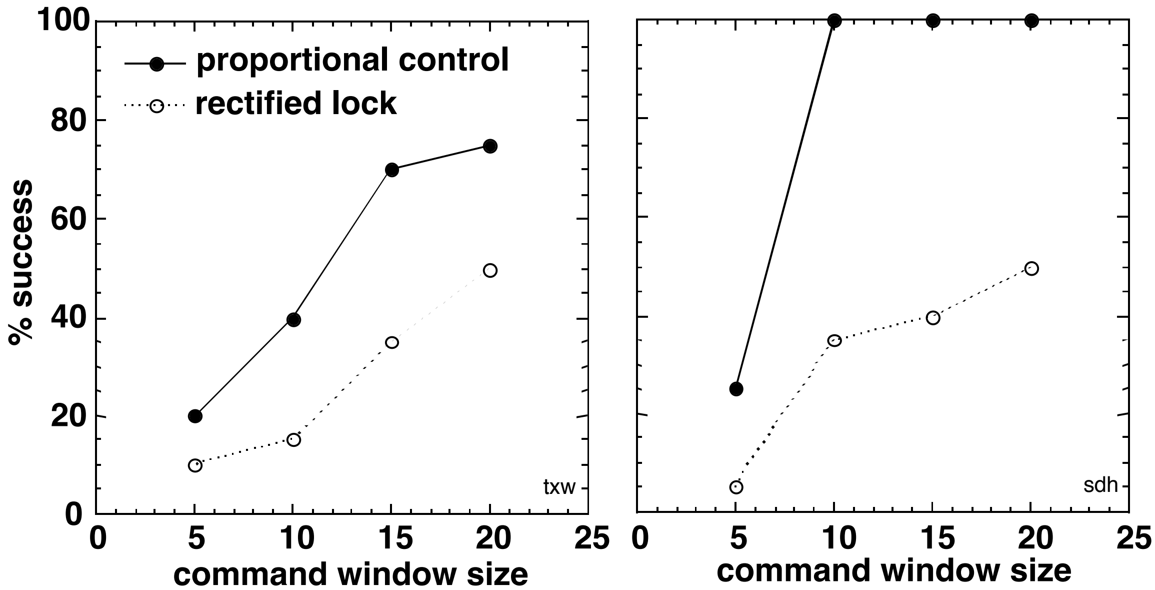


Figure 2.b.ii.2 Performance of 2 subjects (*left* and *right*) on a acquire and hold task using either proportional control or rectified lock control for 4 different command window sizes. Each point is the result of 20 trials.

The results from 2 subjects are shown in Fig. 2.b.ii.2. Each plot shows the percent of successful trials as a function of the command window size for the two different control algorithms. In both cases the performance decreased as the window size was decreased. In this task, the proportional control algorithm enabled better control than the rectified lock algorithm at all window sizes and for both subjects. Most failures with the rectified lock controller were the result of the subject overshooting the target and not begin able to reduce the grasp force within the allotted acquire time.

These results demonstrate that the video based evaluation system is a useful tool in evaluating new command control algorithms, and suggest that rectified lock, in its current form, may not be an improvement over the presently used proportional control.

Plans for Next Quarter

During the next quarter, we will continue to modify the video based evaluation system to incorporate new command control algorithms, and conduct experiments to compare the performance of subjects using new algorithms or traditional proportional control. Further, the problems caused by the time delay, which is an inherent element of the present lock detection method, will also be investigated.

2. b. iii . INCREASING WORKSPACE AND REPERTOIRE WITH BIMANUAL HAND GRASP

Abstract

Four able bodied subjects and one neuroprosthesis user have begun training is using the beta rhythm (18-50 Hz component of the EEG) to control cursor movement on a computer screen. The beta rhythm has been selected since there is little effect of extremity movement upon the level of control, and the stimulus artifact does not contaminate the EEG signal in this frequency range. Three subjects have achieved and maintained a greater than 90% accuracy rate with the beta rhythm. The other two subjects are still in the learning stage, but have started to demonstrate a good level of control.

Purpose

The objective of this study is to extend the functional capabilities of the person who has sustained spinal cord injury and has tetraplegia at the C5 and C6 level by providing the ability to grasp and release with both hands. As an important functional complement, we will also provide improved finger extension in one or both hands by implantation and stimulation of the intrinsic finger muscles. Bimanual grasp is expected to provide these individuals with the ability to perform over a greater working volume, to perform more tasks more efficiently than they can with a single neuroprosthesis, and to perform tasks they cannot do at all unimanually.

Progress Report

In this quarter, four able-bodied subjects and one neuroprosthesis user began training in using the beta rhythm to operate cursor movement. The beta rhythm is the 18 to 50 Hz component of the EEG signal recorded over the frontal cortex. This is a deviation from the protocols developed by Dr. Jonathan Wolpaw, our collaborator on this project. There are two reasons for this change in the protocol. The first reason is that the neuroprosthesis electrically excites the paralyzed muscles with a 12 Hz frequency. Because of this, any recording of a biological signal at the 12Hz frequency is greatly contaminated by the stimulus artifact. The second reason for the change is that subjects are unlikely to be able to control cursor movement (and eventual neuroprosthetic operation) and generate movements of the upper extremity at the same time. This finding was outlined in detail in the last progress report. By recording the beta rhythm, we can avoid the problem with stimulus artifact, and since this signal is being generated by areas of the cortex not directly responsible for extremity movement, there should be little effect of movement on cursor control.

Figure 2.b.iii.1 shows the accuracy rates which have been achieved by all five of our subjects using the beta rhythm. Two of the able bodied subjects and the neuroprosthesis user have achieved a greater than 90% accuracy level after 6 sessions and have been able to maintain that level of control. The other two able bodied subjects are still considered to be in the training phase of the study. They have only completed 3 sessions, yet they are beginning to exhibit significant control over the beta rhythm, achieving an accuracy rate between 75 and 85%. Table 2.b.iii.1 shows the electrode sites from which the beta rhythm is being recorded and the frequency which is being used to control cursor movement for all the subjects. The recording sites are all in the frontal area, and all of the subjects are using a frequency between 25 and 28 Hz for cursor control.

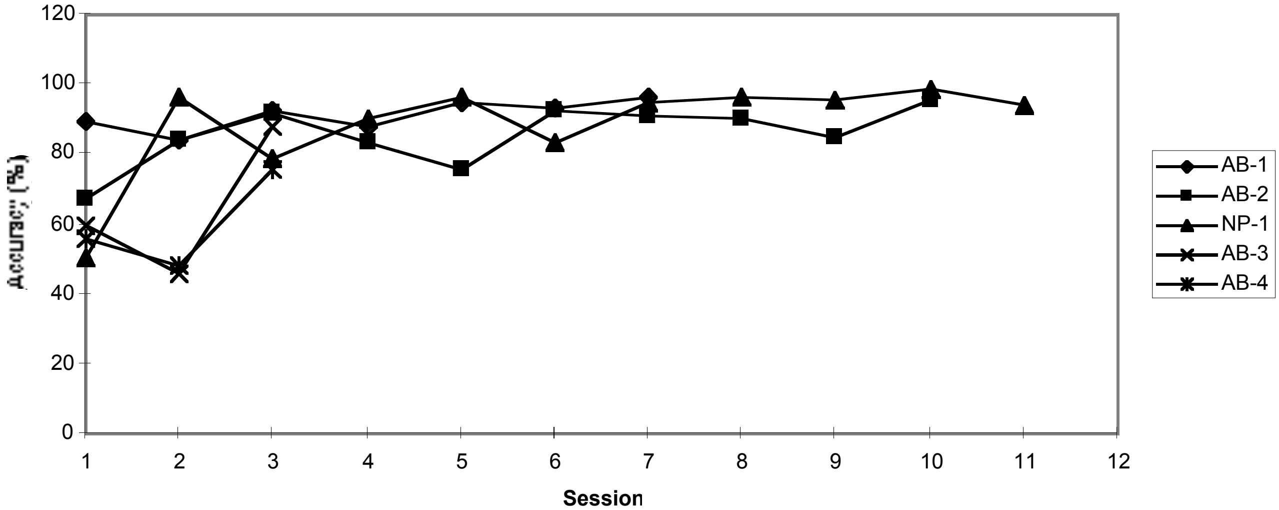


Figure 2.b.iii.1 - Subject accuracy with the beta rhythm control as a function of session number.

Subject	Electrode Location	Frequency	Sessions
AB-1	F4	25 Hz	6
AB-2	FP2	27 Hz	9
AB-3 *	FP2	27 Hz	3
AB-4 *	F3	25 Hz	3
NP-1	F3	28 Hz	12

Table 2.b.iii.1 - Recording sites and frequencies used for each subject in study. The star after the two subjects indicate they are still in the training phase of the study.

The three well trained subjects were then asked to participate in an additional study which was used to confirm that the subjects would be able to control cursor movement and generate movements of the upper extremity at the same time. The subjects were seated in front of the computer monitor. Then, starting with their hand resting in their lap, they had to reach out and grasp a 0.5 kg weight, move it a set distance, release the weight, and return the hand to the lap. This was repeated as many times as possible (the rate of movement set by the subject) while they moved the cursor on the computer screen. This was done for both the right hand and the left hand. The results of this study are shown in Table 2.b.iii.2. The values in the table represent the subjects accuracy rate. As can be seen, there is little change in the subjects accuracy rate between the conditions of not moving, moving the right hand, or moving the left hand. From this, we have concluded that upper extremity movement does not interfere significantly with the cursor movement, and thus can be used as a control signal for upper extremity movement.

Subject	non - movement (% accuracy)	right side movement (% accuracy)	left side movement (% accuracy)
NP-1	94.9	97.5	90.8
AB-1	93.8	95.5	92.6
AB-2	91.5	94.8	96.1

Table 2.b.iii.2: Effect of right and left side movement on cursor control

Plans for Next Quarter

During the next quarter, we will investigate the use of the beta rhythm for neuroprosthetic further by determining whether this is a 'pure' EEG signal or if the subject is actually generating an EMG signal from the frontalis muscles to control cursor movement. Studies will involve using surface recording of the EMG while the subject is generating cursor movement, asking the subject to deliberately generate EMG and examine the effect on the spectra and the surface topographies, and possibly the use on anesthesia of the frontalis muscles and demonstrating the cursor control is maintained. We will also report on an interface to a neuroprosthesis to demonstrate the feasibility of EEG control in this application.

2. b. iv CONTROL OF HAND AND WRIST

Abstract

This aspect of the contract is not active at the present time. Effort is being placed on the experimental measurement of wrist moments and moment arms as described in Section 1A.

Purpose

The goal of this project is to design control systems to restore independent voluntary control of wrist position and grasp force in C5 and weak C6 tetraplegic individuals. The proposed method of wrist command control is a model of how control might be achieved at other joints in the upper extremity as well. A weak but voluntarily controlled muscle (a wrist extensor in this case) will provide a command signal to control a stimulated paralyzed synergist, thus effectively amplifying the joint torque generated by the voluntarily controlled muscle. We will design control systems to compensate for interactions between wrist and hand control. These are important control issues for restoring proximal function, where there are interactions between stimulated and voluntarily controlled muscles, and multiple joints must be controlled with multijoint muscles.